line element method for electrothermal transients in large superconducting coils.

CORE COMPETENCIES

1. Quench modelling
2. Superconductivity
3. FEM

When designing a quench protection system for a superconducting magnet, being able to simulate electrothermal transients can be of great merit. However, when modelling large superconducting magnets – for example for a tokamak – the high aspect ratios in a coil can cause practical hurdles. For example the height of a toroidal field coil can be order of magnitude ~10 m, while the thickness of the cable insulation might be order of magnitude ~1 mm. This leads to time-consuming geometry and mesh construction. Besides this, modelling the cable cross sections in detail means many degrees of freedom and thus computationally heavy models and long iteration times.

In collaboration with UKAEA, we developed a method that avoids such hurdles. Thereby, the cables are approximated as lines with line elements to describe currents, voltages and temperatures (*I, V, T*). In the surrounding domain, the magnetic vector potential *A* is solved for. The method is based on FEM and implemented in COMSOL Multiphysics. Because the method is basically a modification of AV formulation, using an additional variable *I* for the current in a cable we coin this AVI formulation.

We will first show a benchmark where we compare AVI formulation to a detailed model with the full cable cross section modelled using HΦ formulation. We do this for the case of quench propagation along a straight piece of cable. Then we will show an application of the AVI formulation in a simplified toy model.

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Normal zone propagation benchmark

The cable design shown in figure 1 is based on a preliminary design from STEP. The tape stack contains about 200 tapes and its critical current density is *B* and *T* dependent. A background field of 10 T is added, making that the critical temperature equal to 73.8 K which is closer to a practical application of this cable. For the AVI model, the detailed cross section is of course not in the model, but electrical and thermal properties are converted into quantities that are averages over the cross section, for example the current sharing resistance per unit length, the heat capacity per unit length, etc. A quench is initiated by artificially ramping down the critical current density to 0 in a certain region (purple in figure 1).

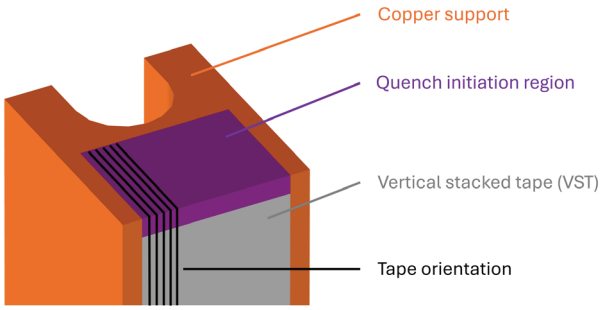

Figure 1 Preliminary cable design from STEP.

The average temperature in the cable cross section is plotted along the cable length in figure 2 for both methods. The time indications are w.r.t the moment that T_c is reached for the first time. The timing of this moment does not align between the models due to the approximation made in AVI: the 3D nature of the current distribution around the normal zone is ignored, and therefore the heating is slower. However, from this moment onwards the agreement is good enough for all sorts of design purposes. And especially so when considering that the AVI model computes in a few minutes, whereas the HΦ model takes a few hours.

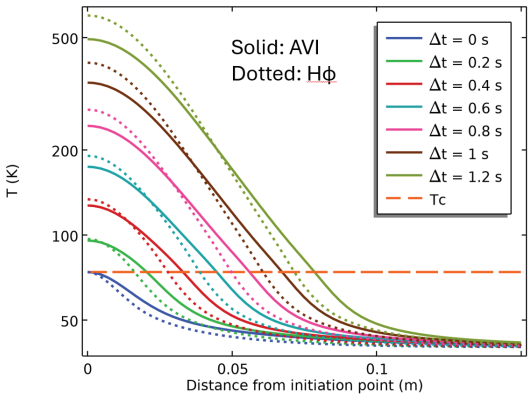

Figure 2 Cross-section averaged *T* plotted along the cable length. Note that mirror symmetry is used to model only one half of the temperature peak.

Toy model: a heater for quench protection

Figure 3 shows a simple 1m x 1m coil that we use to demonstrate the physics of a heater that is used for quench protection purposes. The scenario is a discharge: the current in this coil is ramped down from 90 kA to 0 within 1 ms. Because the inductance of the coil impedes such a fast decay of the flux, that means 90 kA runs through the heater after 1 ms, see figure 4.

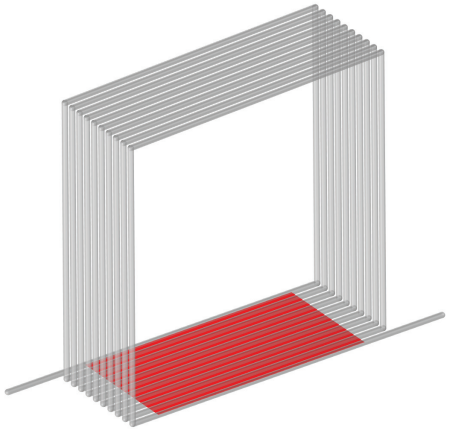

Figure 3 Toy model geometry. Grey: cables, red: heater.

The heater is electrically and thermally connected to the first and last turn, but only thermally to the turns in between. The heater heats up quickly and due to this thermal connection, the temperature in 1 leg of the coil quickly (before all magnetic energy is dissipated) rises above T_c, see figure 5. This makes sure the dissipation is distributed over a sizable part of the coil and not all magnetic energy is dumped in a single hotspot.

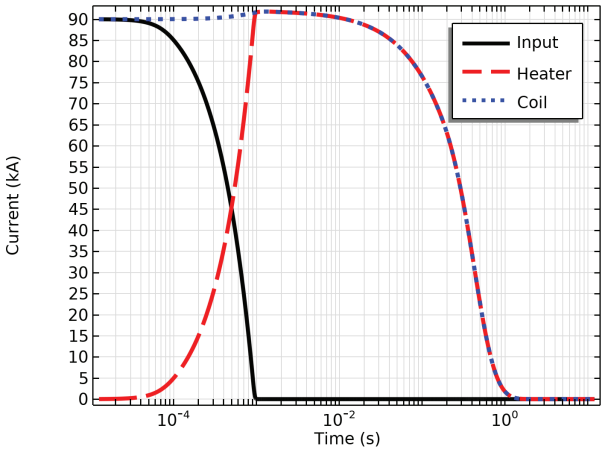

Figure 4 Currents vs time. The current in the coil rises a bit because effectively ~¼ of a turn is not carrying current anymore as soon as the heater has shunted all current, while the flux still has to be the same.

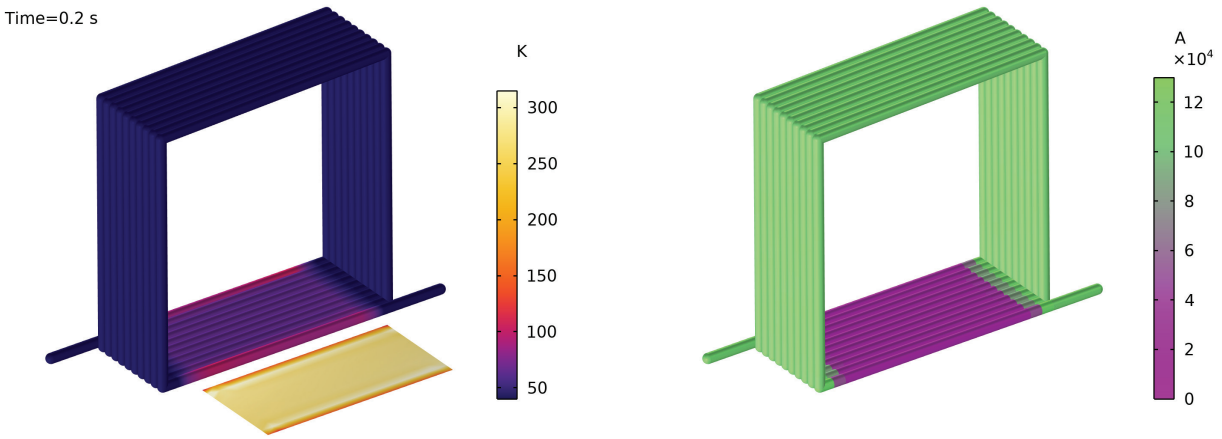

Figure 5 Temperature distribution and critical current at $t = 0.2$ s.

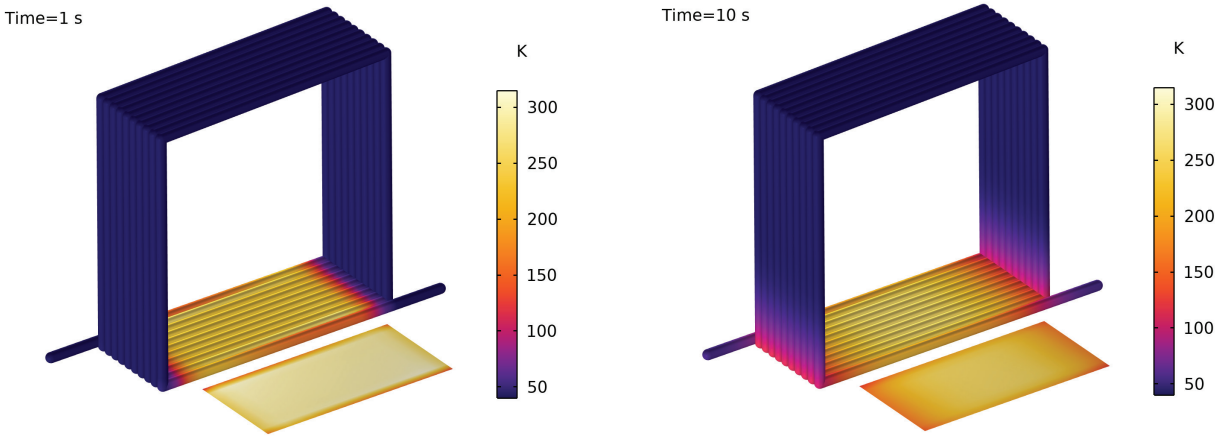

Figure 6 Temperature distributions at $t = 1$ s and $t = 10$ s.

After roughly 1 s (related to the characteristic L/R time of the system) the current has damped out and temperature peaks will only decrease due to thermal diffusion. In figure 6 we can observe the maximum temperature in the cables stays below room temperature.

The example shown here is very simple, but the method can be applied to much more complicated geometries, connecting the line elements to any 2D or 3D structures or external circuits. This way fast iterations are possible, from which many valuable insights can be obtained. UKAEA uses this method for the design of the quench protection system of the toroidal field coils.

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